Collective design in 3D printing: A large scale empirical study of designs, designers and evolution

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COLLECTIVE DESIGN IN 3D PRINTING: A LARGE SCALE EMPIRICAL STUDY OF DESIGNS, DESIGNERS AND EVOLUTION

The last few years has witnessed the rise of the 'Maker Movement', which is often referred as the third industrial revolution and its progression is compared to the early years of the Internet (Anderson, 2012). At core, driving forces behind the maker movement are digital manufacturing technologies. These technologies - such as 3D printing - are called 'disruptive' (Campbell et al., 2011; Lipson and Kurman, 2013; Mota, 2011; Petrick and Simpson, 2013) because they can help break the traditional boundaries between designers and users and enable 'design anywhere, build anywhere model of product development' (Rosen, 2014). With strong ties to open design (Howard et al., 2012), maker movement is a grassroots movement, where all makers are encouraged to share, use and improve each other's designs.

Several platforms have emerged to serve the ever-growing network of makers and designers by providing content, infrastructure or manufacturing capacity as services. On one side, there are cloud manufacturing platforms like Shapeways, iMaterialize and Ponoko, which provide public access to a number of additive manufacturing technologies and provide designers an online market place and an infrastructure to sell their designs without worrying about the actual manufacturing process. On the other side, there are online sharing platforms that were established by hardware (e.g. Thingiverse.com: Makerbot Industries, Cubify.com: 3D Systems, Youmagine.com: Ultimaker) or software companies (e.g. Autodesk 123D Design, GrabCAD) to encourage users to share designs and ultimately support their main lines of businesses. Through these online and distributed environments Collective Design emerges as a paradigm; where designers get inspired by each other and communicate through loosely formed and informal design networks.

Collective design platforms attract large number of users and the underlying digital manufacturing technologies are becoming more and more available. Both as an online phenomenon and as a research area; collective design is still at infancy and its constituents, outreach and potential impact are unknown (Nickerson, 2015; Paulini et al., 2012). We believe that there is a lack of empirical research on what these platforms offer, how they emerge and how they facilitate design activities through the participation of large numbers of users.

This paper aims to address this gap by investigating:

- How collective design platforms are used?
- How designs disperse within communities?
- What are the underlying characteristics of the designs and designers network?

We base our case study on the Thingiverse, which is the one of the most popular collective design platforms in terms of the number of designs and registered users (Figure 1). Based on the metadata of 158,489 publicly available designs and 247,768 registered users that are collected from Thingiverse; our analysis aims to uncover the intrinsic characteristics of the platform, naturally complex design patterns that have evolved through a number of generations, and the underlying network of designs and designers.

1. Background and Related Work

The last two decades witnessed the wide availability of communication technologies and resulting changes in management practices, which have promoted the concept of communities; where participants share knowledge around common interests or job roles (Preece and Maloney-Krichmar, 2005). From the professional perspective, there has been significant work on collaborative design, resulting in a number of online design collaboration tools and professional social networks (Zhang et al., 2007). While similarities can be drawn from research conducted in participatory design (PD), collaborative product development (CPD) and computer supported cooperative work (CSCW); research in collective design is very young and empirical evaluation of the communities and platforms are lacking (Carchiolo et al., 2013; Fuge et al., 2014).

Collective design is an intrinsically collaborative process. The main difference between collaborative and collective design lies within the structuredness of the knowledge and the means of communication. In (Huang et al., 2010), authors distinguish the difference between 'tightly coupled collaborative design' – which requires project management tools and sophisticated coordination mechanisms among participants; and 'loosely coupled collaborative design' – which is based on social protocols and participants' abilities that do not require any explicit coordination. With the rise of the internet, loosely coupled collaborative networks such as Wikipedia (Panciera et al., 2009) have emerged, where people voluntarily self-organize and develop significant intellectual products as an expression of 'radically different types of collective intelligence' (Matthews et al., 2012).

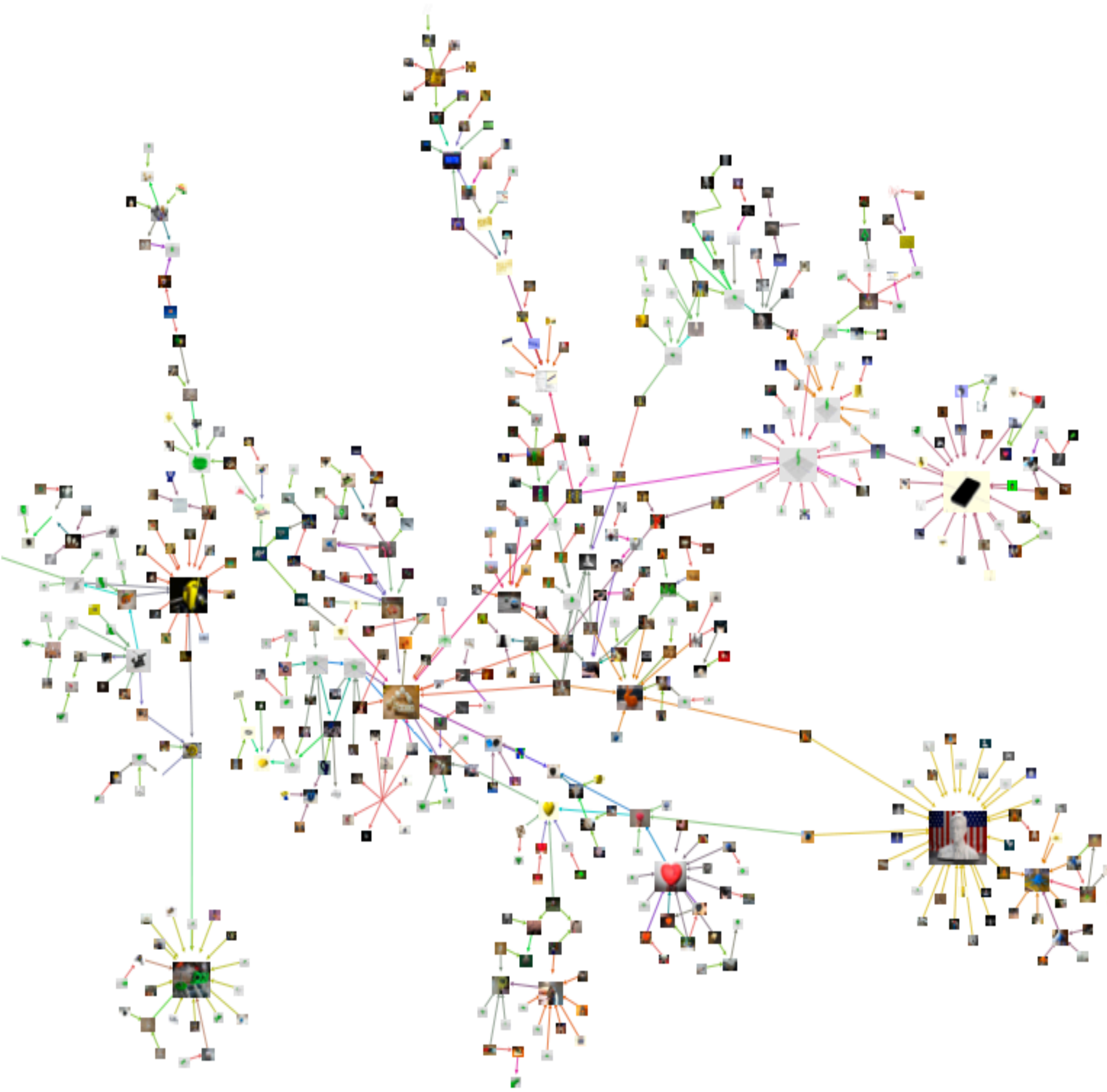

Figure 1,The complex network of designs that is normally hidden within the Thingiverse platform. The figure depicts a small portion of the network that is discovered through this empirical study. The graph is a directed, and the size of the nodes correspond to the number of citations each design has received.

The central concept behind collective design is that the knowledge is dispersed among and collected from many physically distributed professionals and communities (Paulini et al., 2012). It emerges through online platforms, where large numbers of motivated individuals –

both amateur and professional – contribute to a collective intelligence that stem from their mutual communication, collaboration and competition (Maher et al., 2011).

The research in the network aspects of collective design has its roots in software versioning tools, such as exploring topologies of code repositories (Thung et al., 2013), defining metrics for collaboration (Biazzini and Baudry, 2014) and analyzing the impact (Rodriguez-Bustos and Aponte, 2012). The early work in the field focus on definitions and processes (Falzon et al., 1996), cognitive implications (Visser, 1993), and challenges (Moisdon and Weil, 1994); whereas the recent work is more descriptive, aiming to explain the existing phenomena and provide case studies.

With the rise of the internet based collaboration tools design communities have become a topic of interest in design research. In (Hagen and Robertson, 2009), Hagen et al. investigate how communities become a part of design processes through social technologies. They define social technologies as ‘the combinations of mobile and online tools and systems that enable and seek out participation and contributions by users’ and claim that social technologies can be used both as a design tool and as the subject for design. Paulini et al. use three projects from the ‘social product development’ platform Quirky.com as a case study and their analysis of forum communications for these projects reveal that communities are particularly good at contributing to ideation and evaluation phases in product design projects (Paulini et al., 2012). Similarly, Song et al. review the use of social technologies in collaborative product innovation networks, where companies aim to involve a broad range of users within their design and innovation processes (Song et al., 2013). In addition to specific, design oriented online platforms; more generic social networks such as Twitter, are also used as a design collaboration platforms for context-based matching of designers with different skills from different communities (Jung, 2013).

Network analysis tools recently gained popularity within the design research community, in relation to understanding how designers collaborate and communicate in design communities. In (Fuge et al., 2014; Fuge and Agogino, 2014) the analysis of an online and large scale social innovation network is presented, where authors investigate the use patterns and clique formations in the OpenIDEO platform. Network analysis has also been useful for understanding smaller, real-life designer networks in conjunction with protocol studies. For instance, network analysis tools has been used to visualize designer activities (Cash et al., 2014) , derive cognitive maps to illustrate the evolution of concepts and ideas (Kim and Kim, 2015), and design collaborative services to foster community resilience (Baek et al., 2015).

The work presented in this paper differs from the previous work in three major aspects. First, we provide an in-depth analysis of a well established collective design platform; therefore, the amount of data that provides the base for our analysis and findings is significantly larger than other reported case studies. Second, the sheer amount of design and designer data allows us to investigate the evolutionary aspects of collective design, which has not been reported extensively. And last, we report not only on the ways designers can influence large populations, but also on how designs can be consumed by masses.

The rest of the paper is organized as follows. In section 2, we outline the case study on the Thingiverse, describe our framework and explain the methods for data collection and analysis. Next, we present the results of our analysis and provide a detailed picture of the designs, designers, users of the platform. In section 4, we discuss our findings and argue that collective design platforms can provide insights to practitioners and design research community. Lastly, we conclude our research in section 5 and suggest some directions for future work.

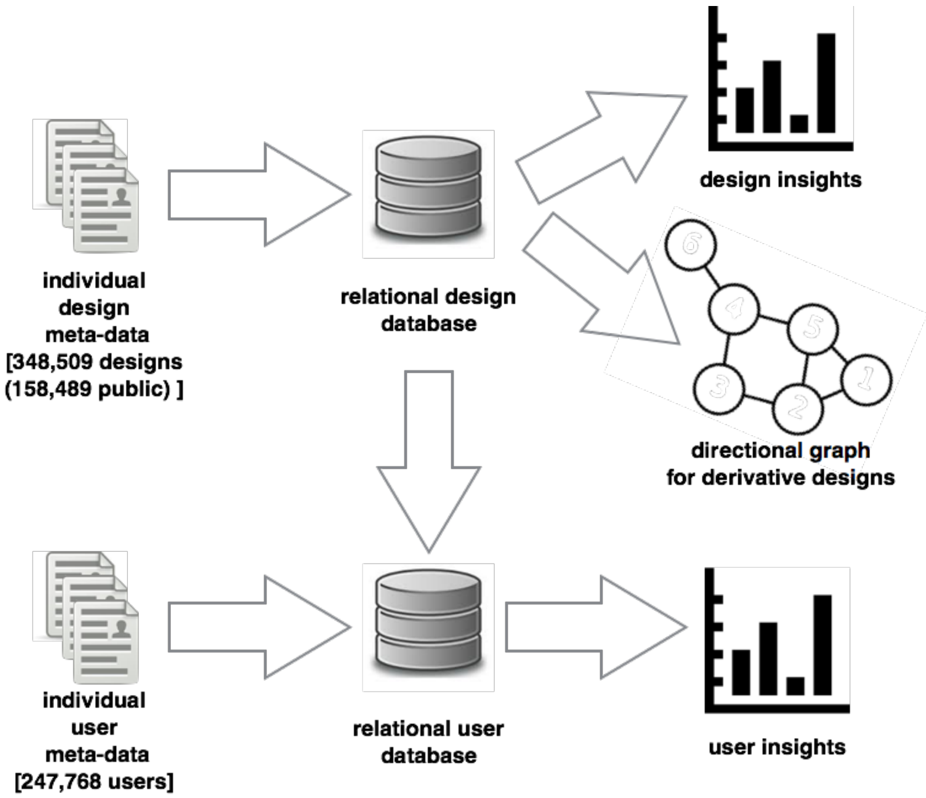

Figure 2, Using the Thingiverse API, we have collected individual design and user meta-data and built relational databases, that are further used for the analysis.

2. Case Study: The Thingiverse Design Network

Thingiverse is founded by MakerBot Industries as a necessity in 2008, since design for 3D printing required specialized training and expensive CAD programs that are geared towards professional use. As it became apparent that the (3D) content was as important as the hardware for the growth; Thingiverse was established as a file-sharing platform so that novice users could easily access community-generated content, and MakerBot 3D printers could be marketed to wider audiences.

Designs or *things* on Thingiverse represent real and physical objects that can be made using digital manufacturing tools (primarily 3d printers). With a few exceptions (explicit content and weapons), Thingiverse allows users to upload digital representations of any physical object.

New *things* can be created in three different ways: By uploading a new design to the repository, by uploading a ‘derivative’ - where an existing object in the public repository is modified or improved, or by uploading a ‘mash-up’ or hybrid- where two or more objects are combined together in a hybrid design.

A typical design consists of one or more STL files that are used for 3D printing, associated source (CAD) files, basic information about the design, instructions for printing/assembly, the license for sharing, pictures and videos of the physical design and references to parent designs – (if it is a derivative or a hybrid). A strong attribution culture exists within the community and the users encourage each other to cite the original designs and the designers they are inspired from.

There are three main reasons why we chose Thingiverse as a basis for our case study. First, it hosts one of the largest design repositories and it has a global and a very active community. Second, it implements the concept of derivatives which enables us to investigate the evolutionary aspects of collective design. And third, it provides (limited) programmatic access to their public repository through an application programming interface (API).

Figure 2 provides an overview of our methodology; we collect meta-data on things and users and then treat and process it to explore insights on the designs, designers and the evolution of the platform. The following sections describe these steps in detail.

Table 1, The structure of the metadata collected from the public repository of the Thingiverse

Thing *meta-data*		
Name	Text	Name of the design
ThingID	Num	Unique ID of the design
**CreatorID*	Num	Unique ID of the designer
DateAdded	Date	Date of creation
Description	Text	Basic Description of the design
Instructions	Text	Instructions for manufacturing / assembly, print parameters
FileCount	Num	Number of associated files
Categories	Enum (Text)	Which pre-defined categories this design belong to?
**Ancestors*	Array (Num)	What are the Parent Designs – if any?
License	Enum (Text)	Which license is used for sharing?
User *meta-data*		
username	Text	User name
userID	Num	Unique ID of the user
regisrationDate	Date	User's registration date
lastActiveDate	Date	Date of last activity from the user
**Location*	Text	(optional) Location of the user in human readable form

2.1. Data Collection and Analysis

Using the Thingiverse API, we have crawled the individual meta-data files for all publicly available things and users on the platform. Table 1 summarizes the extent of the available meta-data that is used for analysis. In total, 3.2Gb of data for 348,509 designs (158,489 public, 149,078 private, 40,942 deleted) and 247,768 users is collected.

Only open source tools are used for data collection and analysis: Networkx (Hagberg et al., 2004) for network construction and analysis, Numpy (Van Der Walt et al., 2011) for statistical analysis, BeautifulSoup (Richardson, 2008) for parsing web pages, Matplotlib (Hunter, 2007) for data visualization and Python as the general programming framework.

The analysis of the raw data deals with two relational databases we have built for things and users (Figure 2). These databases are used to compute the descriptive statistics and gather insights on how collective design is manifested on the platform.

Three fields from the meta-data (Table 1) are further processed for generating additional meta-data; in order to reveal the network graph, identify the designers and map the user locations:

> **Ancestors**: Thingiverse only provides information on immediate parents and children of the designs therefore the information on the family trees of designs is not explicitly available. In order to compensate for this shortcoming; we have traversed the design database and built a network representation of the things by creating links between parent and children designs based on the information provided in the 'ancestors' field. The resulting directional graph is used to analyze and understand how designs emerge and disperse within the community.
>
> **CreatorID**: User database provides information on all users of the platform: Both users whom have submitted designs (designers), and users whom have only used the platform. Using the 'creatorID' field of the design database we have derived the list of designers and compared it to the user database. This is further used to explore the correlations between creation and consumption of the designs on the platform.
>
> **Location:** Users have the option to provide their location during registration. There are no restrictions on the formatting of the location data therefore it is not usable for analysis in raw format. To levitate this; we have utilized Google's online geolocation service to geocode the sparsely formatted location names into a list of latitudes and longitudes. This data is used to render the geographic distribution of the users.

2.2. Design Evolution Trees

Understanding the collective behavior and the concurrency of the development processes requires a representation for how designs are topologically connected to each other. This information is only implicitly represented on the Thingiverse therefore we first had to construct the network graph from the raw data as explained above.

There are evolutionary aspects that are reflected within derivative design networks. In order to better understand these aspects of the collective design, we define Design Evolution Trees (DET) - which are phylogenetic trees (Darwin, 1859) that stem from root designs and branch through multiple generations of derivatives (as illustrated in Figures 1, 3 and 11) .

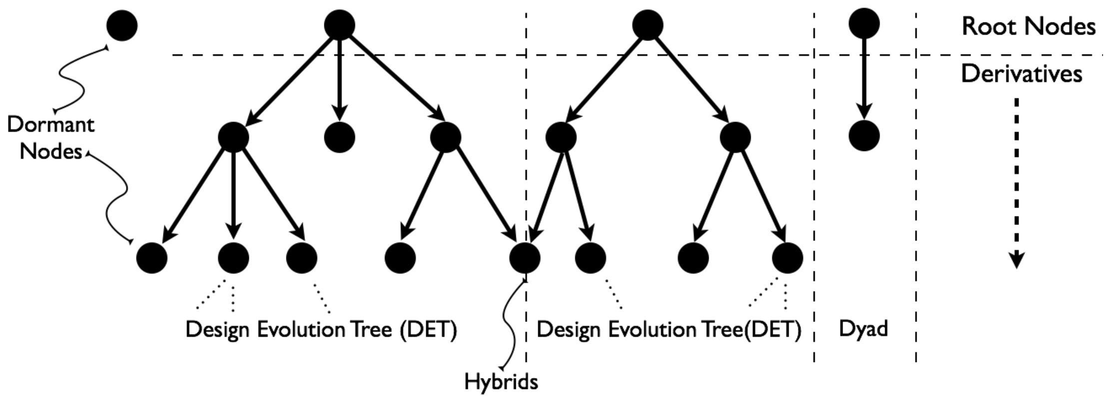

Figure 3, Design Evolution Trees are implicitly formed trees, as designers get inspired from each other and upload new designs to the platform, that are derived from existing designs.

Typically roots represent original designs or early prototypes that have the potential to be embraced and further developed by the community. Derivatives stem from other designs. While uploading derivatives, users have the chance to indicate from which things their designs are derived from. If a design cites multiple parents, it is considered to be a hybrid.

The final stage of our analysis deals with the identification of the DETs. By utilizing the directional graph that is derived from the things database; we first identify the root designs, and then recursively trace the connected derivatives.

2.3. Limitations of the data

The metadata for the designs that are submitted to Thingiverse are (partially) manually entered by the users; therefore, errors and inconsistencies due to user input are carried over to the analysis. Furthermore, what constitutes a derivative is open to interpretation. The network shows how designs are derived over the time, but it does not reveal to which degree a derivative is different from or similar to its parents. For instance, we have observed some users uploading minor revisions of the same design, and effectively using derivatives as a versioning tool, as Thingiverse do not support it natively. Similarly, there could be a possible attribution bias if a hybrid design has many parents; as the designers can cite the designs they are inspired from, without specifying what features of the parent design are transferred to the hybrid.

Almost 41,000 things have been deleted since the inception of the Thingiverse. While most of the removals were made by the users themselves, some of things were removed by the Thingiverse due to intellectual property infringement claims (Howells, 2014). Our dataset does not reveal which things have been removed and their real impact on the design network is unknown; but there is a possibility that some graphs might have been split into to partitions due to deleted nodes.

Similarly, there are a large number of private things that do not reveal any parent/children information. Their influence on the network is also unknown; but we presume that most private things are either dormant original designs or dormant derivatives.

3. Results

Users and things are the central sources for the descriptive analysis of the raw data, whereas derivatives are used to uncover the complex evolutionary patterns that lead to the emergent collective behavior (Figure 1) in the platform.

The following sections outline our findings on the users, designs, derivatives, hybrids and DETs; and uncovers how the Thingiverse collective design platform is used, how designs disperse within the community and what are the underlying characteristics of the designs and designers.

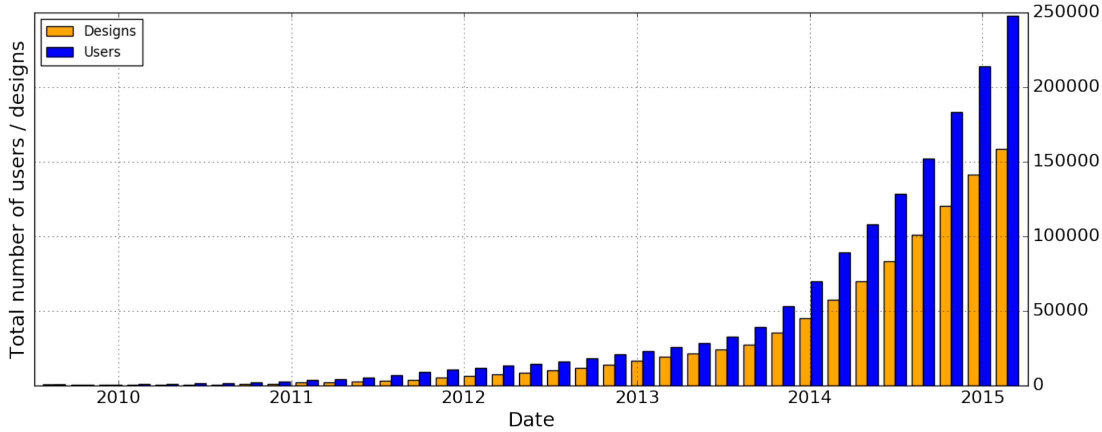

Figure 4, Thingiverse is one of the largest collective design platforms and it has been growing exponentially in the last few years; as 3D printing has become a mainstream technology

3.1. Users

As shown in Figure 4, the user base of the Thingiverse has been growing exponentially in the past few years, and our dataset has information on 247,768 registered users.

Not all users of the platform are designers. In fact, comparison of the creatorIDs (from things database) to the *users* database reveals that only a small portion of the users (n=38,867 / 15.6%) are content creators (designers). Figure 5 illustrates the further analysis of the contributions of the designers to the platform (On average - 4.05 designs per designer).

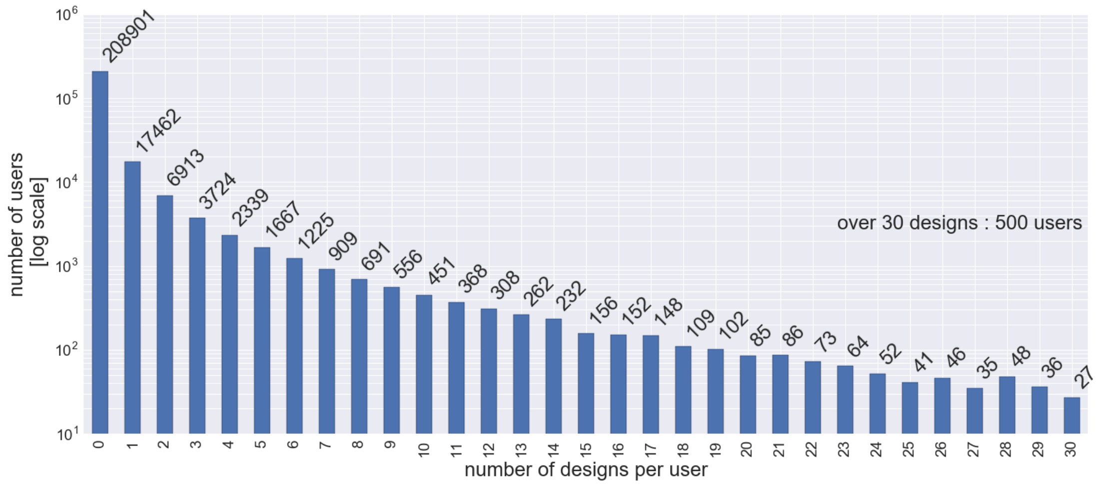

Figure 5, Contributions of the users to the platform; vast majority of the users have not contributed any designs – only 15.6% of the users are designers.

3.2. Things

The things database has information on 158,489 designs that are publicly available on Thingiverse. We have also identified 149,078 private and 40,942 deleted designs, which do not have any meta-data. Figure 4 shows the growth of the platform over the time, with a rapid increase in the number of designs and users in the past two years.

Open design culture is very strong among the users of the Thingiverse; as illustrated in Figure 6, the vast majority of the publicly available things can be copied, edited and redistributed per Creative Commons (CC) licenses.

All CC licensed designs require that the original design and designer must be credited (Attribution) and designers can further choose to include the three possible conditions: ShareAlike (sa) – which mandates that the derived work has to have the same license conditions as the parent design, NonCommercial (nc) – which prohibits the use of the designs for commercial purposes without the permission of the designers and NoDerivatives (nd) - which only allows the copying and distribution of the original work. Most CC designs on Thingiverse has various combinations of Attribution and ShareAlike and only 13.8% of the CC licenses prevent commercial use of the designs.

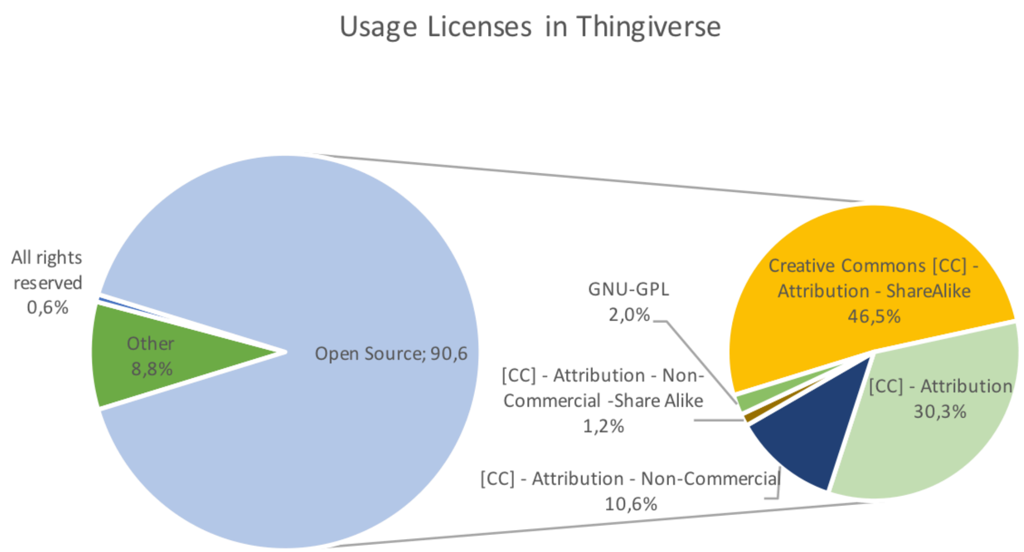

Figure 6, Open Design has a significant presence on Thingiverse: 90.6% of all things have Open source licenses Creative Commons or GNU licenses.

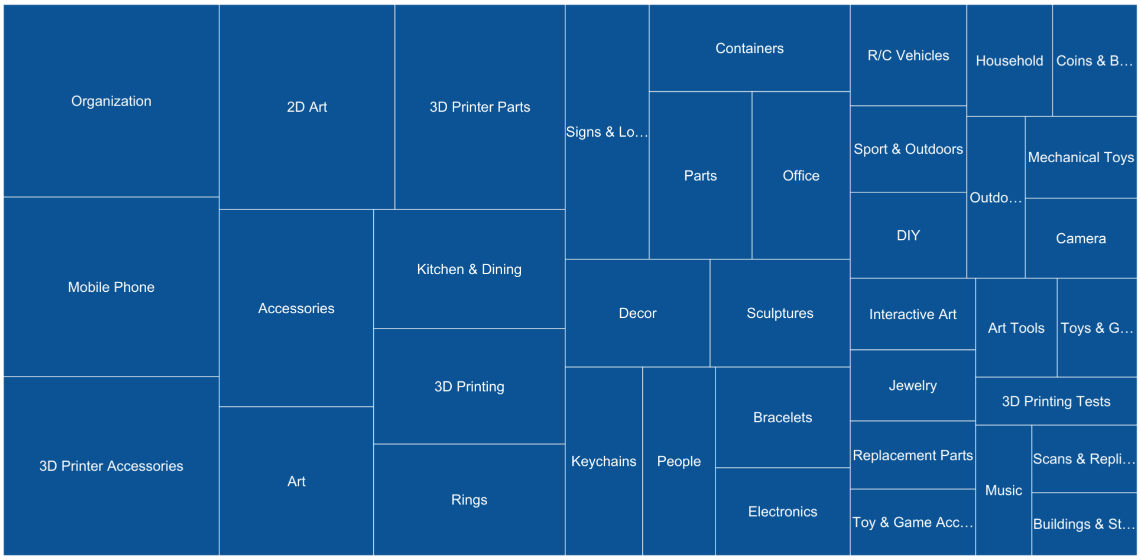

Figure 7, Tree-map representation of the dataset reveals the popularity of the top 40 predefined categories: The Size of the boxes represent the relative popularity of the categories on the Thingiverse.

The analysis of the categorical design meta-data reveals the core interests of the design community. The tree-map in Figure 7 shows that the most popular categories are related to 3D printing (parts, tools, accessories), mobile device cases, holders and accessories, organizers (key chains, storage boxes, holders) and art-related objects (3D figures, sculptures.).

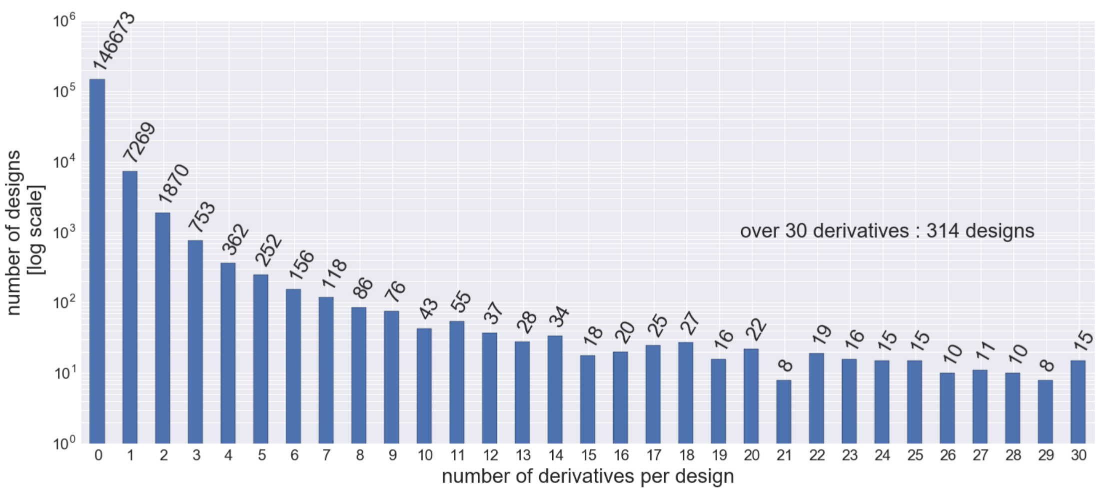

Figure 8, Distribution of the number of derivatives per design. Even though the majority of the designs on Thingiverse have been dormant; the remaining designs have spurred more than 51% of the whole network.

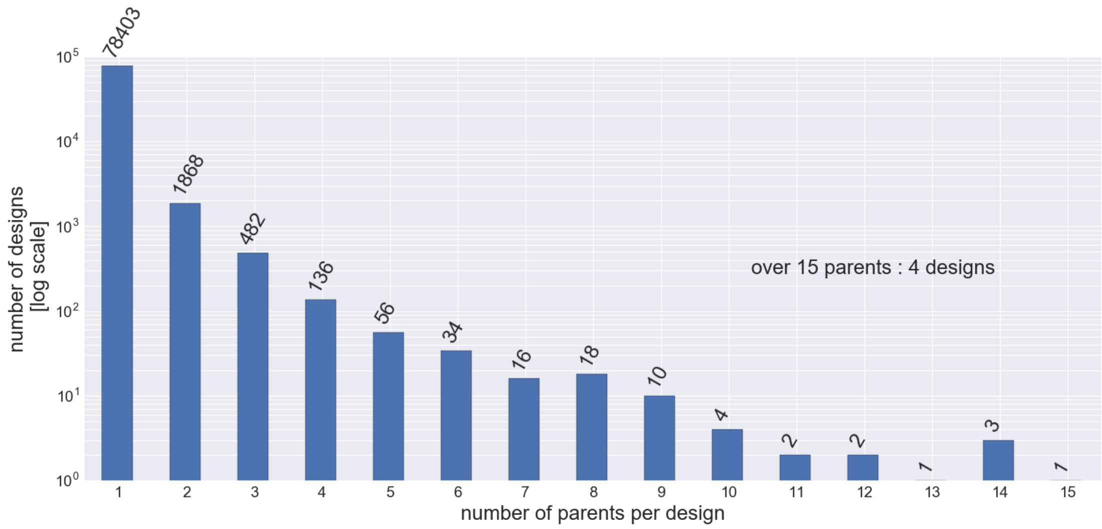

Figure 9, Distribution of the number of parents per design. Hybrid designs only represent %1.7 of the network.

3.3. Derivatives, Hybrids and Fertility

Understanding how collective design manifests itself within the Thingiverse and how designs disperse within the community heavily rely on the analysis of the derivatives and hybrids.

Typically, derivatives are improvements and adaptations of a previous design that stem from a single parent, whereas hybrids borrow features or elements from multiple parent designs. Original designs refer to designs that are not related to other designs on the platform and therefore they do not have any parents.

The concept of derivatives can also be associated with fertility: A fertile design has at least one successor in the form of derivatives or hybrids. Designs that do not have any successors are considered to be dormant.

Table 2, Summary of the fertility of original, derivative and hybrid designs

	Dormant Designs	*Fertile Designs*	Total
Original Designs	69,340 | 43.7%	7,994 | 5.1%	*77,334 | 48.8%*
Derivative Designs	75,568 | 47.7%	2,835 | 1.8%	*78,403 | 49.5%*
Hybrid Designs	1,765 | 1.8%	871 | 0.55%	*2,636 | 1.7%*
Total	*146,673 | 92.6%*	*11,700 | 7.4%*	*158,373*

Table 2 is derived from the network representation of the design database and it summarizes our analysis of derivatives, hybrids and fertility. There are three main conclusions:

- The vast majority of the designs have been dormant and the overall fertility of the network is very low. But it should be noted that the platform has only recently experienced a significant growth (Figure 4), and newer designs might lead to derivatives in the future.

- The concept of 'derivatives' play a central role in Thingiverse. Despite the low overall fertility of the network, more than 51% (n=81,039) of the designs are derivatives and hybrids. Figure 8 looks at derivatives closer and reveals the distribution of the number of derivatives per design. 'Lithopane' (thing:74322) is a customizable design and it has the highest number of derivatives (n=5,246) in the network.

- Hybrid designs only represent a very small portion of the network; but their relative fertility is much higher than that of derivatives (33% vs 3.7%). Most hybrids have two parents but hybrids with three or more parents are not uncommon (Figure 9). 'GOLF-IN-MINIATURE: The Desktop 18 Hole Miniature Golf Course' (thing: 24670), has the highest number of parents is which integrates different aspects from 21 designs.

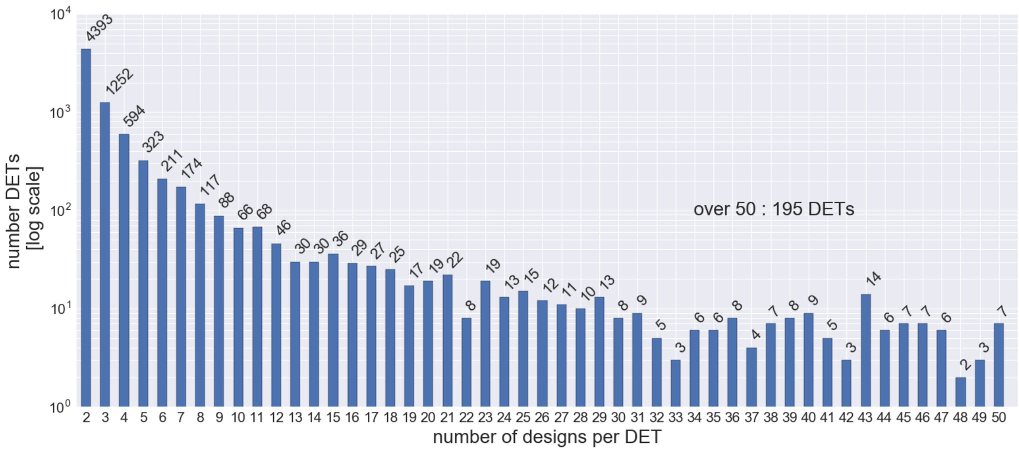

Figure 10, Distribution of number of designs per design evolution tree (DET). The majority of the DETs are dyads

Table 3, Only a small number of designers have initiated design evolution trees, which span 51% of the design network

	Root Designs	*Derivatives & Hybrids*	*Original & Dormant Designs*
Number of Designers	3,991	24,703	20,045
Number of Designs	7,994	81,039	69,340

3.4. Design Evolution Trees

Approximately half of all things on the Thingiverse are original designs (n=77,334), but the vast majority of these designs have been dormant and have not formed a tree yet. The remaining 7,994 fertile, original things (5% of the network) has led to the formation of a complex and intertwined network of DETs spurring 81,309 derivations. Excluding dyads, which constitute more than the half of all DETs (Figure 10), the average fertility rate of root designs is 21.36.

DETs are significant parts of the platform and it is also important to investigate the designers that are involved in their creation and growth. Root designs are the fertile and original designs that have the largest impact on the growth of the platform; and we have identified 3,991 designers whom initiated DETs (Table 3). If we compare the number of designers of the root designs to the number of designers of the derivatives (excluding self-citations); it can be seen that each designer of a root design reaches to an audience of 5.6 designers through the evolution of their DETs.

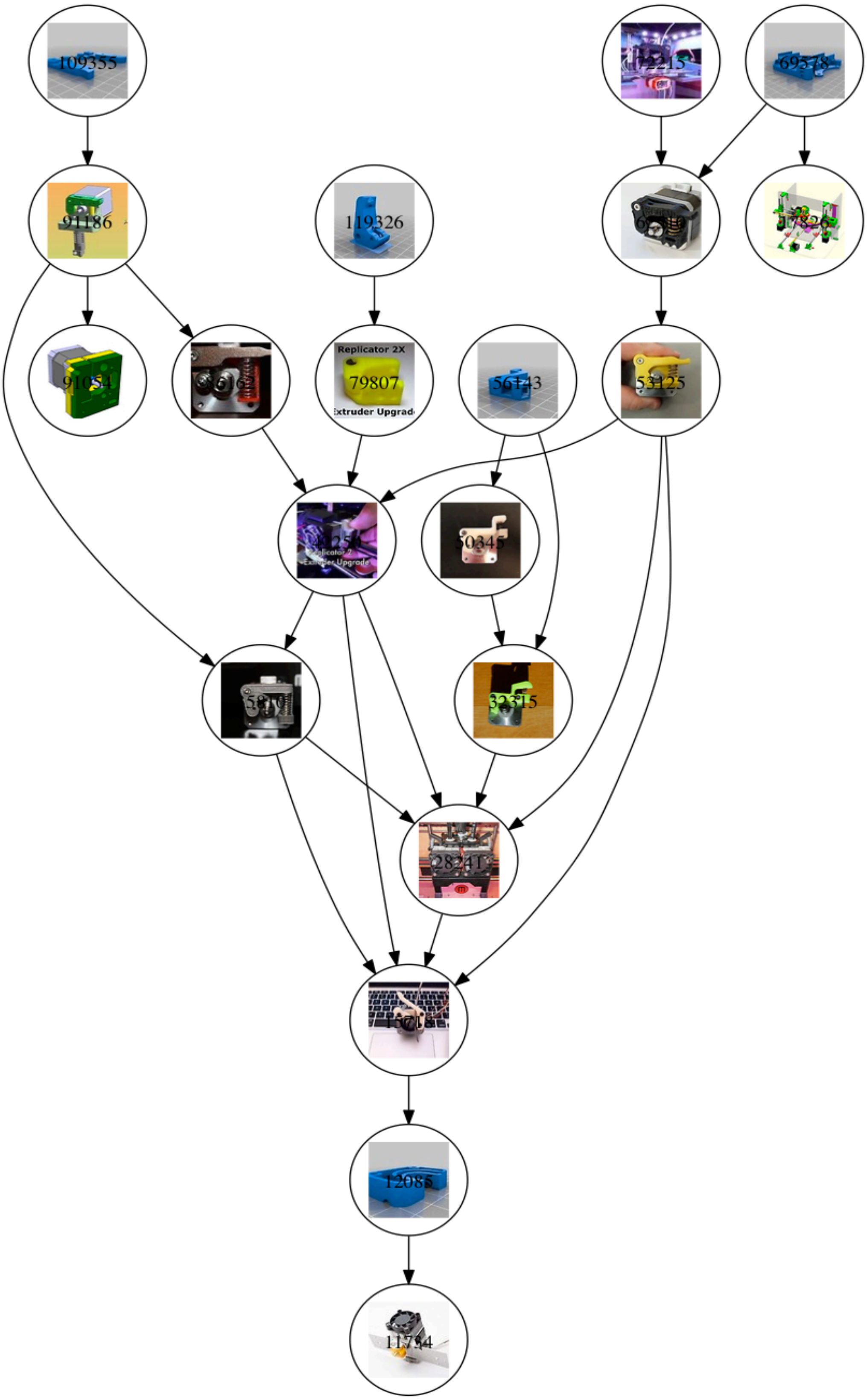

Figure 11, Collective design can lead to rapid evolutions: The Design Evolution Tree shown above illustrates the evolution of an electromechanical extruder, where 17 designs emerged from the original design 'MakerBot Stepstruder MK7' over a span of 19 months. (thing:11734)

4. Discussion

Results presented in the previous section provide a deeper understanding of the designs, users, designers and how collective design takes place on the Thingiverse platform. Based on these findings; we discuss four main topics of insight and provide suggestions for improving collective design platforms.

It should be noted that, there exists a broad range of collective design communities with different goals, target audiences, business models and organizational structures and the discussion presented in this section cannot be universally generalized. While these platforms facilitate collectivity in different ways, such as design challenges, discussion groups or features that enable the users to 'like' and 'collect' each other's designs, a significant part of the discussion presented in this section depends on the concept of 'derivatives' and being able to trace the hereditary features of the designs. For instance, Thingiverse, Autodesk 123D and OpenIDEO has mechanisms that allows designers to explicitly refer to the parent designs they are inspired from and the following discussions on the evolutionary and open-source characteristics of the design networks mostly apply for these types of collective design platforms.

4.1. Evolutionary characteristics of collective design

Analogies between biological evolution and product development processes has been a topic of interest in design research, where evolution has been defined as 'gradual development, permanent adaptation, and continuous optimization towards an aim that may also change itself during the evolution' (Kittel et al., 2011; Vajna et al., 2005). As our analysis illustrates, evolution is a very strong aspect of the collective design activity on Thingiverse and there are similarities between evolutionary mechanisms and the ways designs emerge.

The concept of derivatives that allows designers to build on top of each others' work is tightly coupled with the strong sharing and attribution culture, and we consider these two elements to be central to the concurrent and evolutionary nature of the collective design on Thingiverse. Designers cannot explicitly see the evolution of the designs, and the role of DETs is largely hidden. But the impact of derivatives on the network is still very significant: 51% of all designs are derivatives and they can be traced back to 8,072 root designs.

The primary way derivatives emerge is comparable to asexual reproduction; as the vast majority of the derivatives are derived from a single parent (Figures 8 and 9). These derivatives typically signify refinements or adaptations to parent designs. A small number of hybrid derivatives exemplify sexual reproduction, where features and inspirations from multiple parent designs are combined together in the hybrid design.

Finally, the formation and the growth of DETs can be compared to the process of natural selection. Collective interests of the community arise as large number of individuals independently show their interest on particular designs, produce derivatives from them and increase their fertility.

4.2. Quick Evolutions and Trivial Designs

Collective design can lead to innovations that materialize rapidly through distributed, asynchronous and a large network of users (e.g. Figure 11). Derivative designs emerge as the network grows, and the evolutionary mechanisms come into force; but the uncontrolled growth also can also have adverse effects. As collective design lacks the structure of collaborative design practices such as common goals, formation of teams and direct communication between team members; a lot of novice designers' effort can go into repetitions.

The tree-map in Figure 8 shows the relative distribution of all designs in 80 pre-defined categories. A quick inspection of the categories reveals the significant interest of the community in personal accessories (rings, bracelets, jewelry), mobile phone related designs (e.g. covers), art and décor. To a large extent, these can be defined as phatic objects (Bosque, 2015); which are usually ornamental and have limited functionality or complexity. Blinkstein coins the term 'keychain syndrome' to describe the interest of the new members of the maker community in phatic objects (Blikstein, 2013). He argues that the users whom are introduced to new digital manufacturing tools like 3D printers and laser cutters tend to value the resulting products rather than the process, which leads them to simplify the technical aspects of design and focus on trivial objects.

We believe that this is not a negative aspect of collective design; but rather a feature of it. The element of play or personalization of the objects like mobile phone covers, key chains and necklaces attracts masses to collective platforms. To some, these rather simple designs can also act as a proxy to learn the necessary design and process knowledge and contribute to the platform as designers and lead users.

4.3. Consumption of, and Contribution to Collective Design

Collective design is a broadly inclusive process, where the majority of the participants are consumers of the design processes and their outcomes. This is consistent with other online communities, where the majority of the members are defined as 'lurkers' - silent participants whom observe and benefit from the community (Katz, 1998; Nonnecke et al., 2006; Nonnecke and Preece, 2001; Preece et al., 2004). Lurking is not necessarily a negative behavior; for many users, it is a chance to learn from the design community and eventually contribute to the collective knowledge when they feel ready to do so.

The reasons mentioned in (Katz, 1998; Nonnecke and Preece, 2001) include being uncomfortable in public, desire for anonymity, communication overload, getting to know the group and lack of time and they probably also hold for collective design networks. In contrast to other online communities, like social networks or discussion boards; participation in collective design platforms might also require technical knowledge or design expertise.

On the other hand, one could also argue that many of those users are simply getting inspiration from other designs and designers or they choose not to engage in collective design for various reasons. As the means for digital manufacturing become more and more accessible and CAD tools improve in terms of their availability and usability; it can be expected that more users will participate in design activities.

4.4. Characterizing the Lead Users

Von Hippel (Von Hippel, 1986) defines lead users as users whom face needs that will be general in a market place much earlier than the general audience, and whom are positioned to benefit significantly from obtaining solutions to those needs. The concept of 'lead users' is associated with gaining customer insights and it is commonly used in traditional product development context (Lettl, 2007; Lin and Seepersad, 2007; Von Hippel, 2009, 1986).

Recently, the do-it-yourself (DIY) and maker culture has become a topic of interest within the design research community; as understanding the participants of these movements can provide insights into customer needs and innovations in various industries (Hahn et al., 2016; Kuznetsov and Paulos, 2010; Waller and Fawcett, 2014; Wolf and McQuitty, 2011, 2015) . (Hahn et al., 2016) further discusses that DIY practitioners can be regarded as lead users and opinion leaders within their communities; since their motivations align well with the conditions laid out in the traditional definitions, they act as innovators and they participate in knowledge sharing within their communities.

Our analysis of the users of Thingiverse reveal that the majority of the publicly available designs on the platform can be traced back to a rather small number of designers. We argue that, these designers can be characterized as lead users; as they initiate evolutionary processes within the platform, create the momentum needed to attract the attention of other designers and lead the way to the collective wisdom.

Whether these lead users have formal training or expertise in design or engineering disciplines remains unknown; but we claim that they at least possess 'designerly ways of knowing' (Cross, 2001, 2006)- such as the ability to frame design solutions, that are not shown by novice users.

Users from developing countries can be also be considered as lead users. Innovation is traditionally linked to economic growth, competitiveness and progress (House, 2011; Judge et al., 2015) and often associated with developed countries. On the other hand, recognizing users from developing countries as lead users can be the key for reverse innovation as designers can understand their latent needs and create globally disruptive innovations by serving these markets (Judge et al., 2015).

4.5. Suggestions for improving collective design platforms

Visibility of Design Evolution Trees

The implicitness of the DETs is one of the most important shortcomings of the platform presented in our case study. There is a very rich body of design knowledge that is carried on the graph representation of DETs, but the users and designers can only see the immediate ancestors and predecessors of a designs.

Making DETs visible can also help to motivate the users and designers to participate more in the discussion and design activities. Most collective design platforms are built upon the idea of sharing knowledge for social incentives rather than economic ones. DETs do not only represent how designs evolve, but they also illustrate how designers provide inspiration to each other.

The effects of the visibility of DETs are not studied in this work, but we believe that it warrants future research to investigate whether novice designers could benefit from seeing the hereditary features and improvements that are carried over through multiple generations of the designs.

Design Versioning

As collective design platforms grow into huge databases, versioning becomes a critical need for the users. While Thingiverse do not provide versioning tools, we have observed that some of the users upload slight modifications of their own designs as derivatives instead of updating their original designs. A proper versioning tool such as the one implemented in Autodesk 123Design could help the users to organize designs in a better way, and increase the overall quality of the designs on the platform.

Reference Designs and Component Libraries

Collective design community has a significant interest in mobile phone covers, tablet holders and an array of other accessories that are designed to interface with existing products. A lot of effort goes into replicating the reference designs and components through manual measurements or 3D scanning, despite the fact that a lot of vendors provide cad models of their products on their websites. We believe that providing the users with a reference library for common products and components would benefit the users and also mitigate dimensioning errors that come from imprecise measurements.

Recommender systems and metrics for innovative designs

If we consider *design* as a search process, collective design can surge the boundaries of the solution space, at the expense of extending the duration of the search. Currently, collective design platforms offer basic search functions but we believe that there is a need for recommender systems that can highlight innovative and influential designs through combined metrics. As the platforms and databases grow, the visibility of the existing designs and users replicate similar designs without noticing each other’s work. Other platforms such as online shopping sites, video streaming services or academic databases that suffered from similar problems has successfully implemented recommender systems. These systems can make the search in collective design platforms more effective, help the users to spot interesting designs and accelerate the innovation process.

Tools for collaboration

Collective and collaborative design do not need to be mutually exclusive. We believe that collective design platforms can adopt tools to facilitate team building, communication, task delegation and versioning for the designers whom would like to collaborate with each other. With such tools in place, complex and multidisciplinary designs can be achieved easier, in a collaborative way.

5. CONCLUSION

This paper presents an analysis of he Thingiverse; with the aim of understanding how collective design occurs on the platform and how designs disperse through loosely connected network of designers.

The first part of the analysis is on the users; it illustrates the rapid growth of the platform in the recent years, reveals where the users come from, distinguishes the users from designers and provides an overview of the how productive the designers have been. Next part focuses on the designs and reveals what the platform is mostly used for, which design categories are the most popular and how open-design has a dominating presence. The third part provides a detailed review of the derivatives and hybrids and investigates the fertility of the designs. Finally, the last part of the analysis explores design evolution trees, reveals their central importance to the platform and exposes that a small number of designers can create a large large impact through the evolutionary mechanisms of the collective design.

The results of this study do not only provide empirical insights on how collective design is manifested on Thingiverse, but they can also be used as probes for further exploitation of the rich data that is available in these type of platforms. Focusing on the users and designers; future works could evaluate the use of collective design platforms to identify the lead users of subpopulations, along with incorporating the geolocation data to uncover latent needs of from different regions.

There are many aspects of the evolution and the fertility of designs, that are not covered within our analysis. For example, it is expected that more generic and easily customizable designs (e.g. phone cases) will have high derivative counts but fewer generations; whereas more specialized designs could have fewer derivatives that are evolved over multiple generations. Designs that have evolved through multiple generations should hypothetically converge to optimal solutions whereas hybrids should achieve higher degrees of innovation by combining the gene pool of multiple DETs. Future work can pinpoint these potentially interesting designs and validate whether evolution in collective design yield to optimal solutions.

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